Micro-Nano Technology

From Micro to Nanotechnology

A perspective from the Semiconductor world
A presentation to CMIC

Jose A. Maiz

Parque Tecnologico de San Sebastian

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Some remarkable quotes

"I think there is a world market for maybe five computers."
Thomas J. Watson, IBM chairman, 1943

“There is plenty of room at the bottom”. “I am telling you what could be done”. “We are not doing it simply because we haven’t yet gotten around to it”. “There may even be an economic point about making things very small”

Richard Feynmann @ the 1959 Annual mtg of the American Physical Society at the California Institute of technology. Transcript available from the California Institute of Technology

“With unit costs falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components in a single silicon Chip”

Gordon E. Moore, Electronics Vol 38, No 8 April 1965

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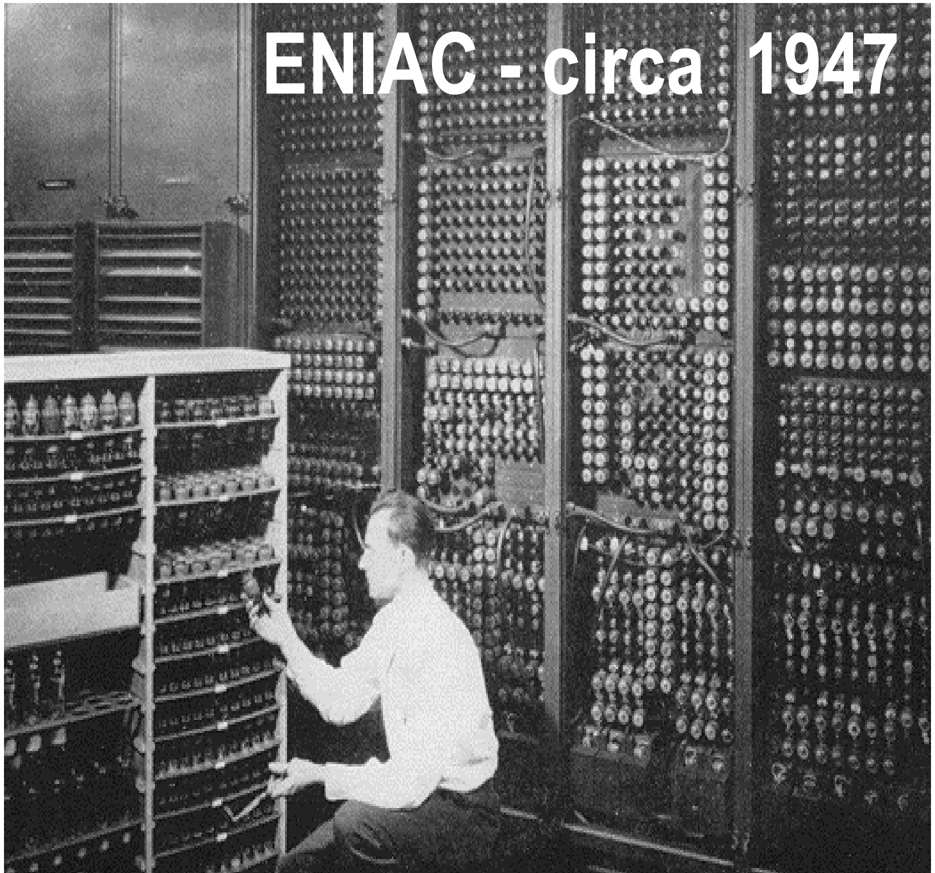
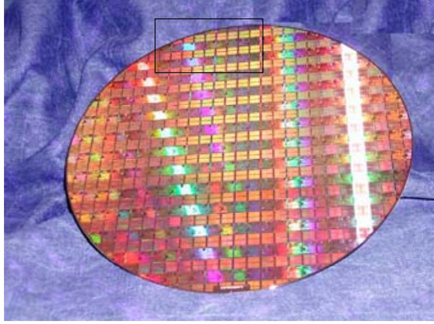
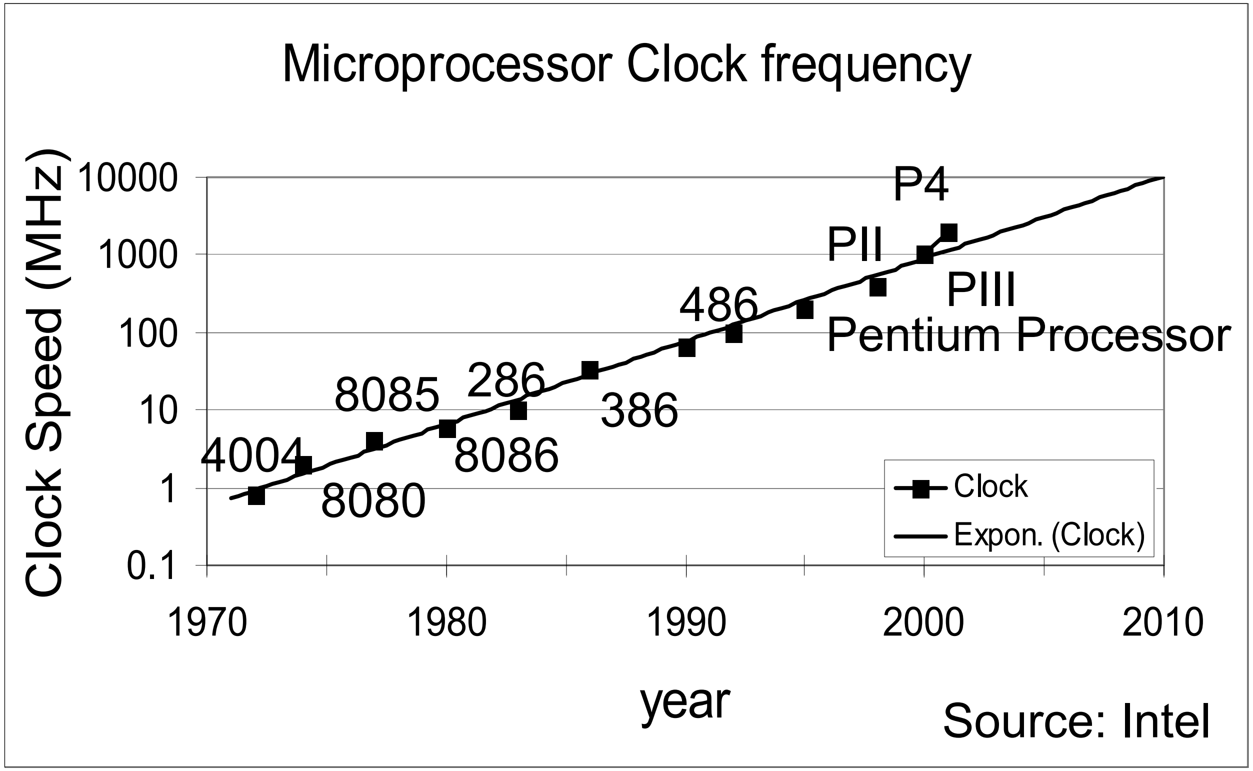


Courtesy of Williams @ HP Labs

- Shrink by 10^8
- Improve power efficiency by 10^8

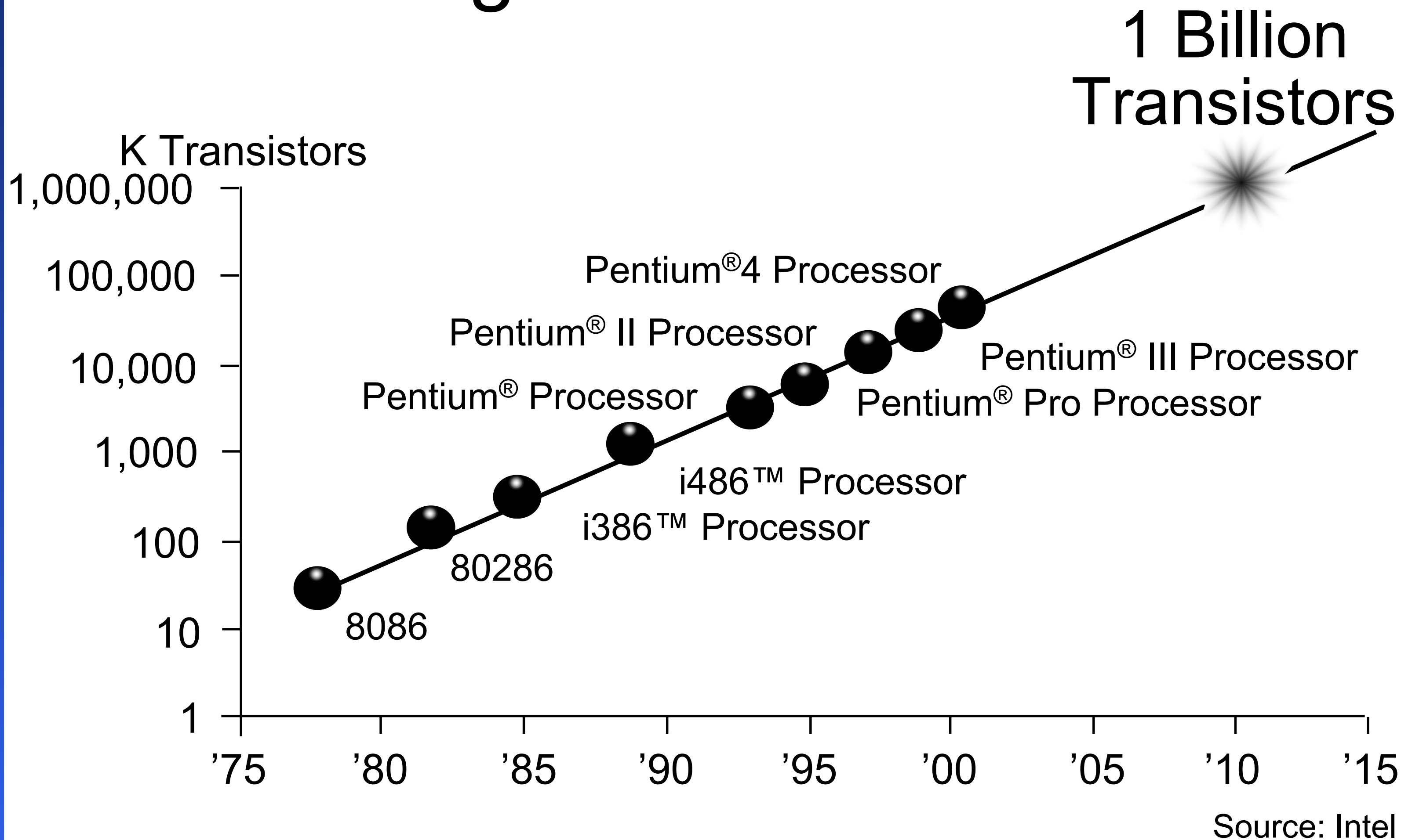
Clock speed trend for microprocessors





- 10GHz projected clock frequency by Yr 2010
- Historical rate: ~2X every 3 years

Scaling of transistor count



- Transistor count increases ~2X every 18 months
- ~ 1000 Million transistors/chip by Yr 2010

And the trend goes on…

- So, what does it take to continue this trend?

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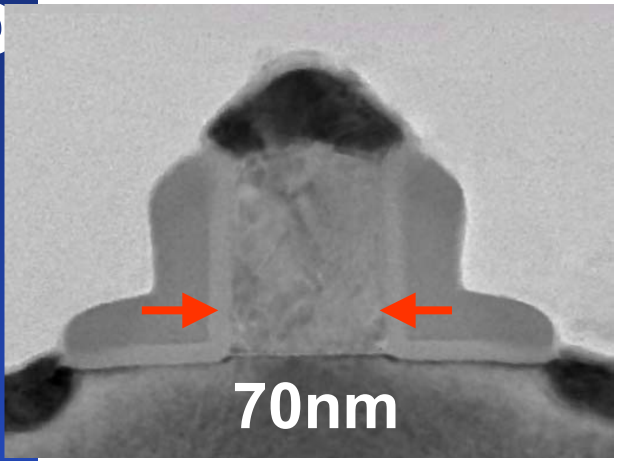
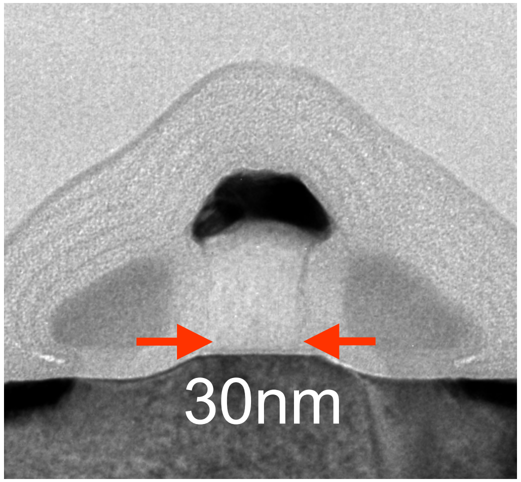
Transistor Scaling

Human hair: ~ 100,000 nm



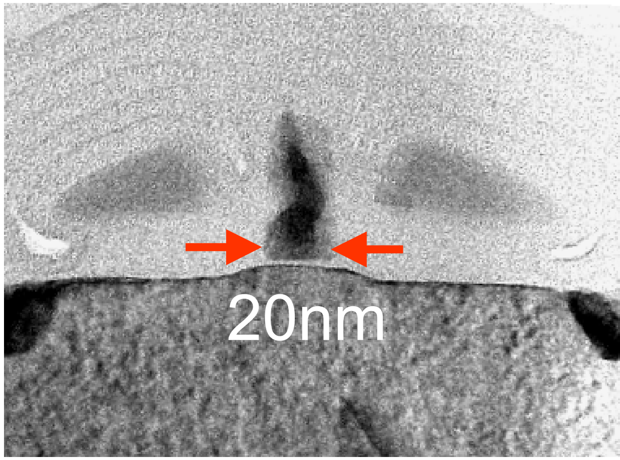
70nm transistor
for 0.13µm process
2001 production

Demo: 2000



30nm transistor
prototype

Demo: 2001

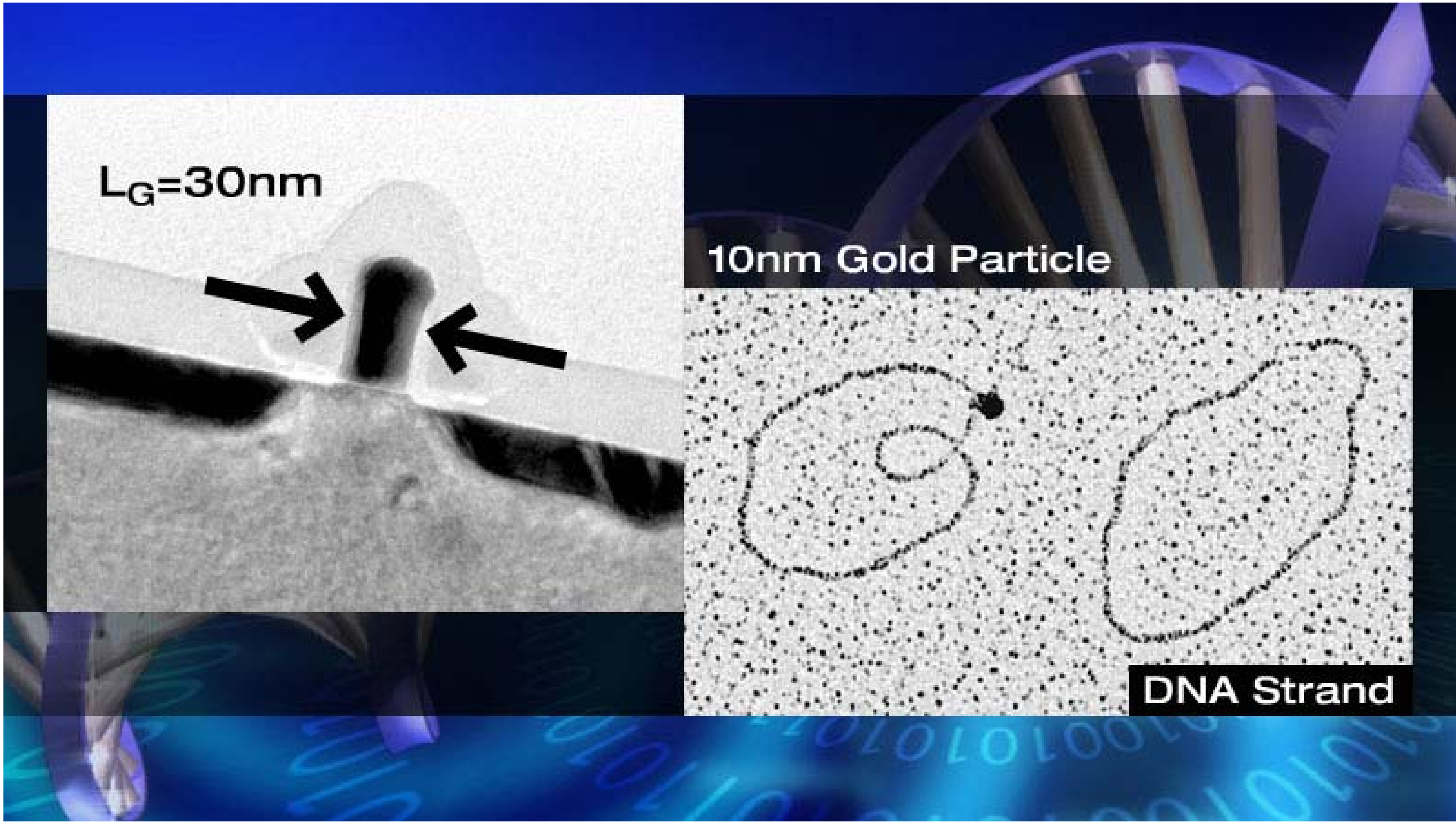


20nm transistor
prototype

Source: S. Chou, R. Chau, Intel

Looking
3 generations ahead

Information on terahertz transistor: www.intel.com/research/silicon



Transistor dimensions are approaching the dimensions of biological molecules

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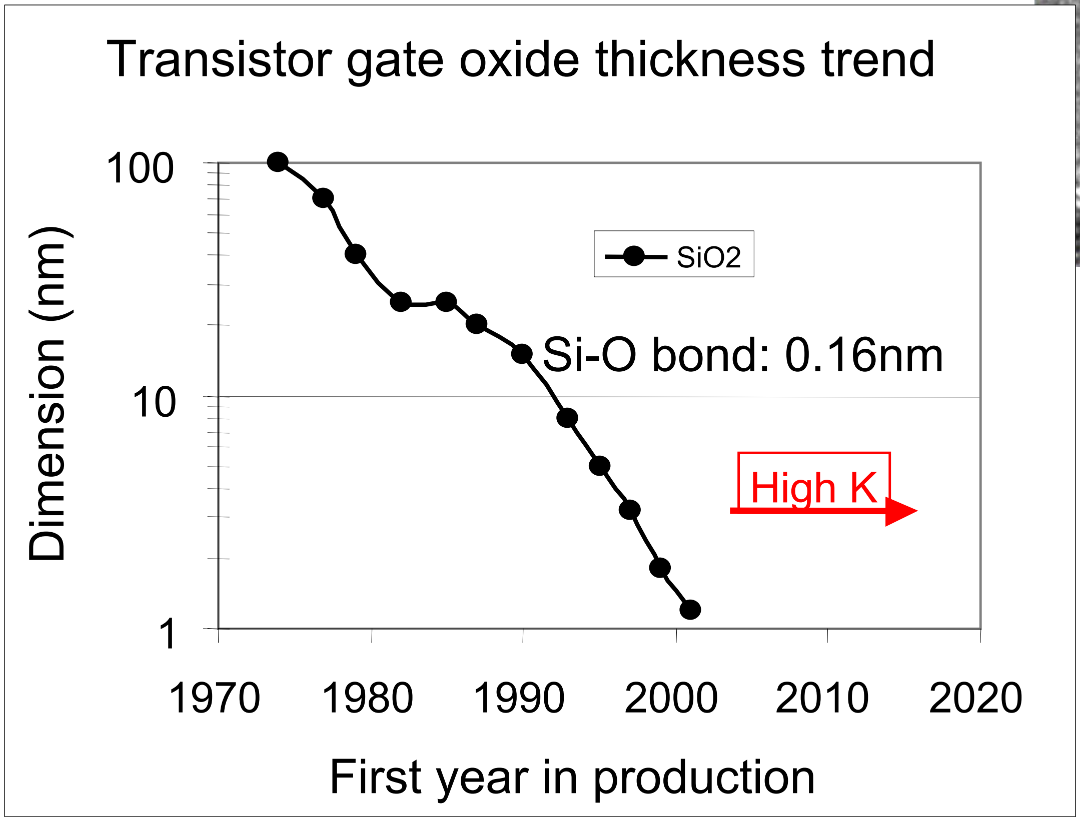
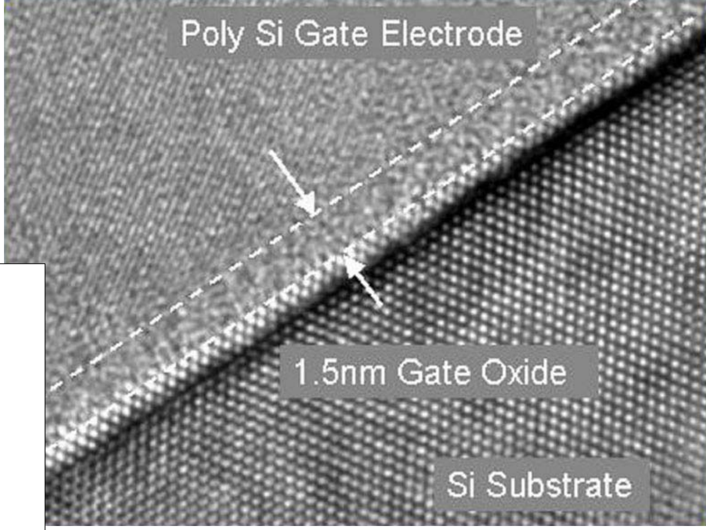
Transistor Gate Oxide scaling trend



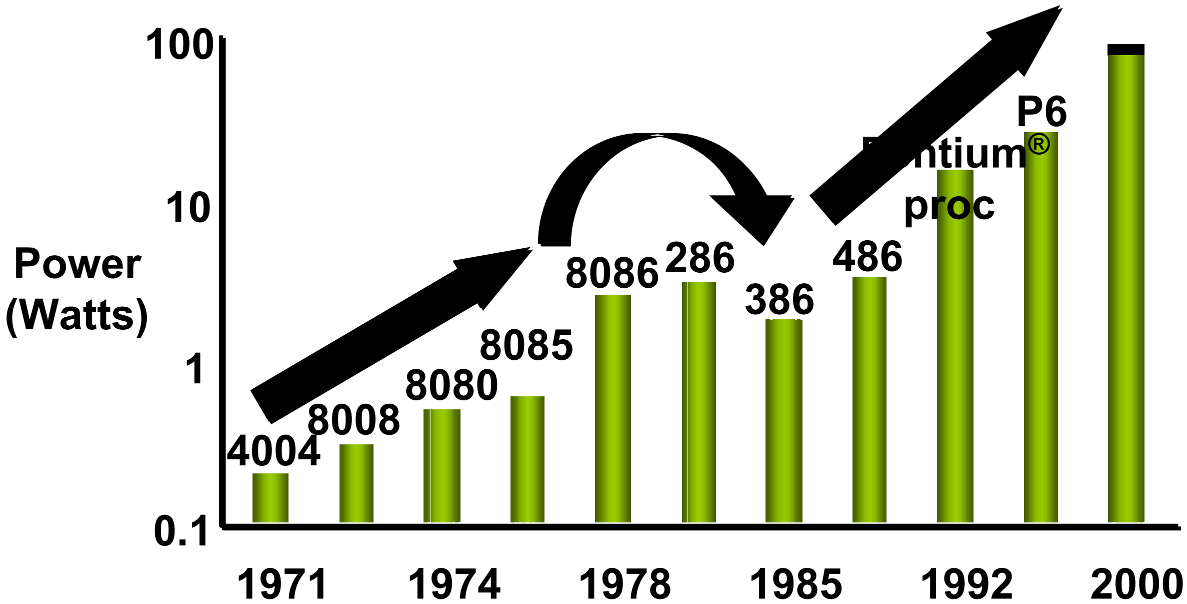


Source: Intel

We have operated for a long time in the nanometer regime

- Scaling ~ 0.65X per technology generation (2 Yr)
- Scaling limited by leakage below 1nm.
- High K dielectrics required for continued scaling

And power grows exponentially…



Source: Intel Architecture Labs

~ 100W/cm2

- Need cost effective package options to:
  - ➤Deliver the power
  - ➤Extract the heat
- Huge challenge and a significant opportunity

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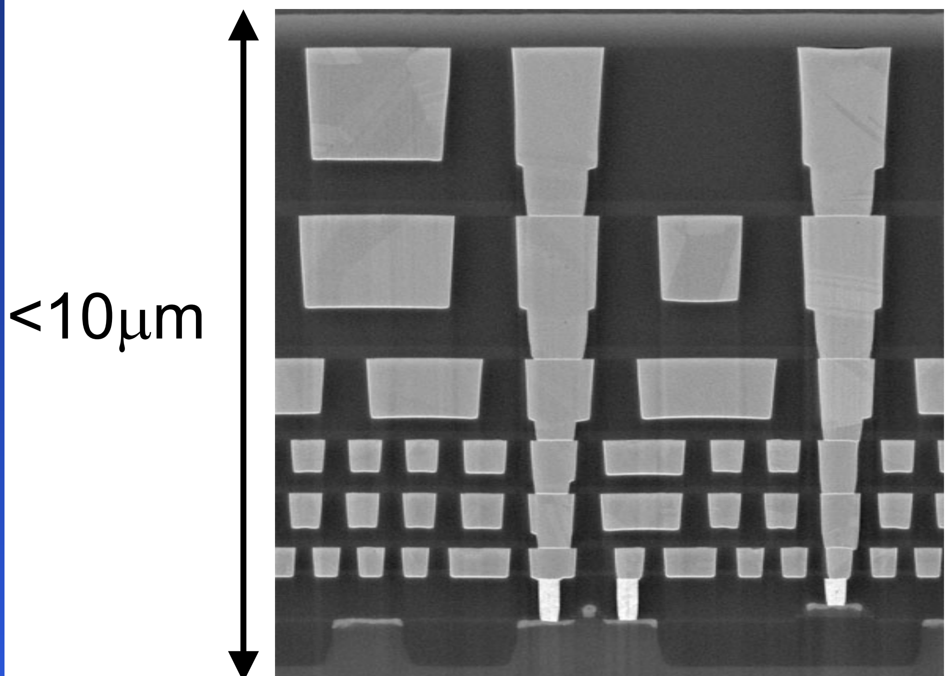
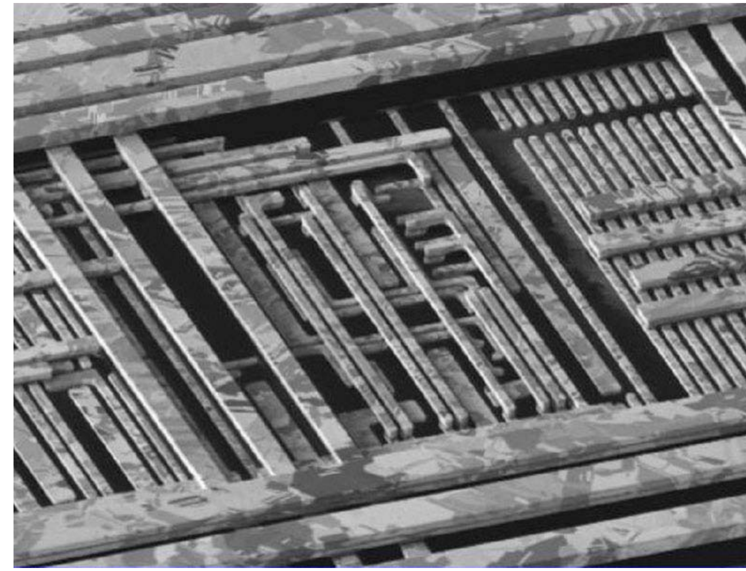
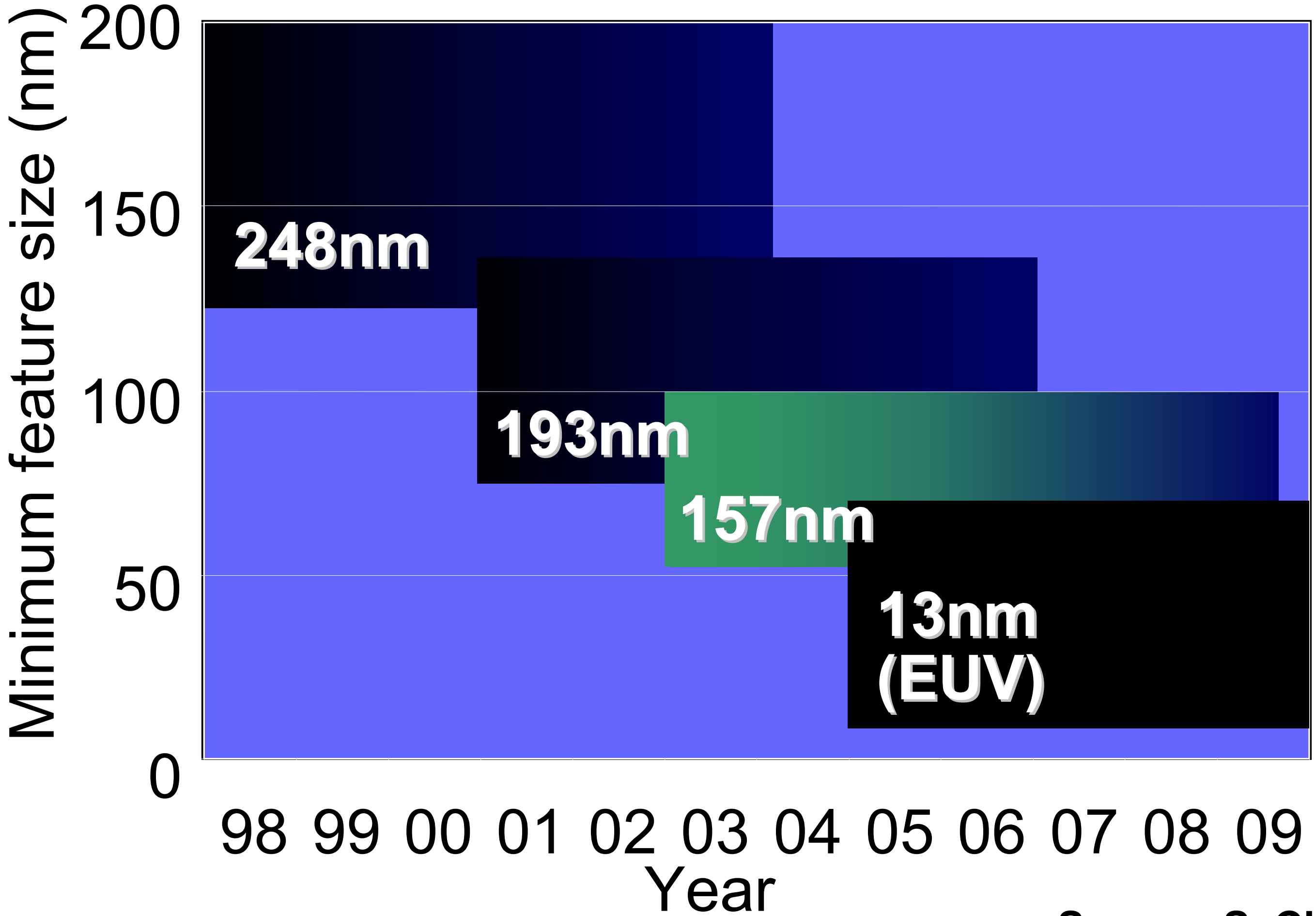
Interconnects are getting more complex





- 6 Layers of copper for the 0.13 um technology
- Low K interlayer dielectrics for reduced capacitance
- The resistivity of copper increases for widths < ~ 100 nm

Lithography roadmap

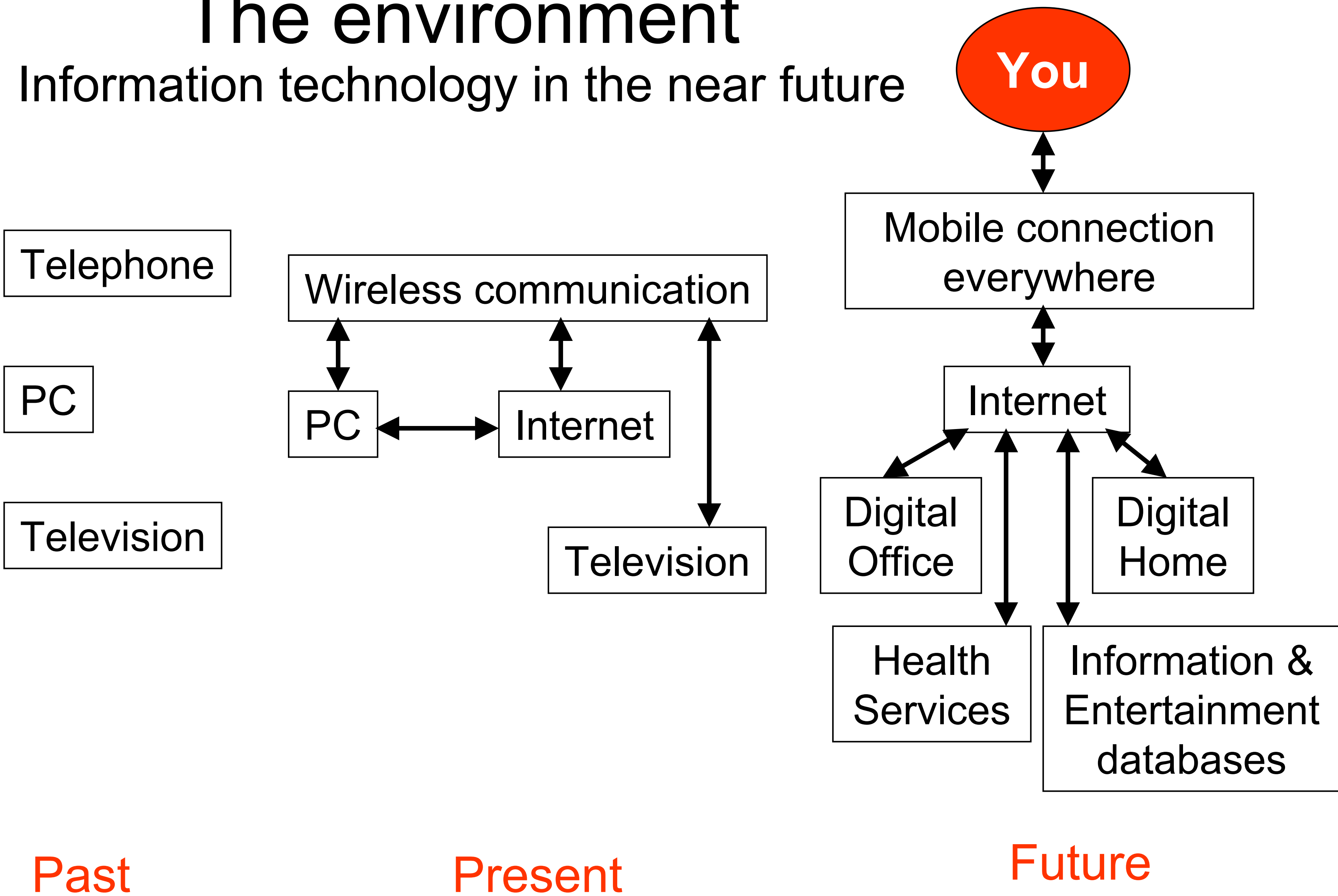


Source: S. Chou, Intel

- Extreme UV (13 nm) will support scaling well into the next decade but at an increased cost

The environment

Information technology in the near future



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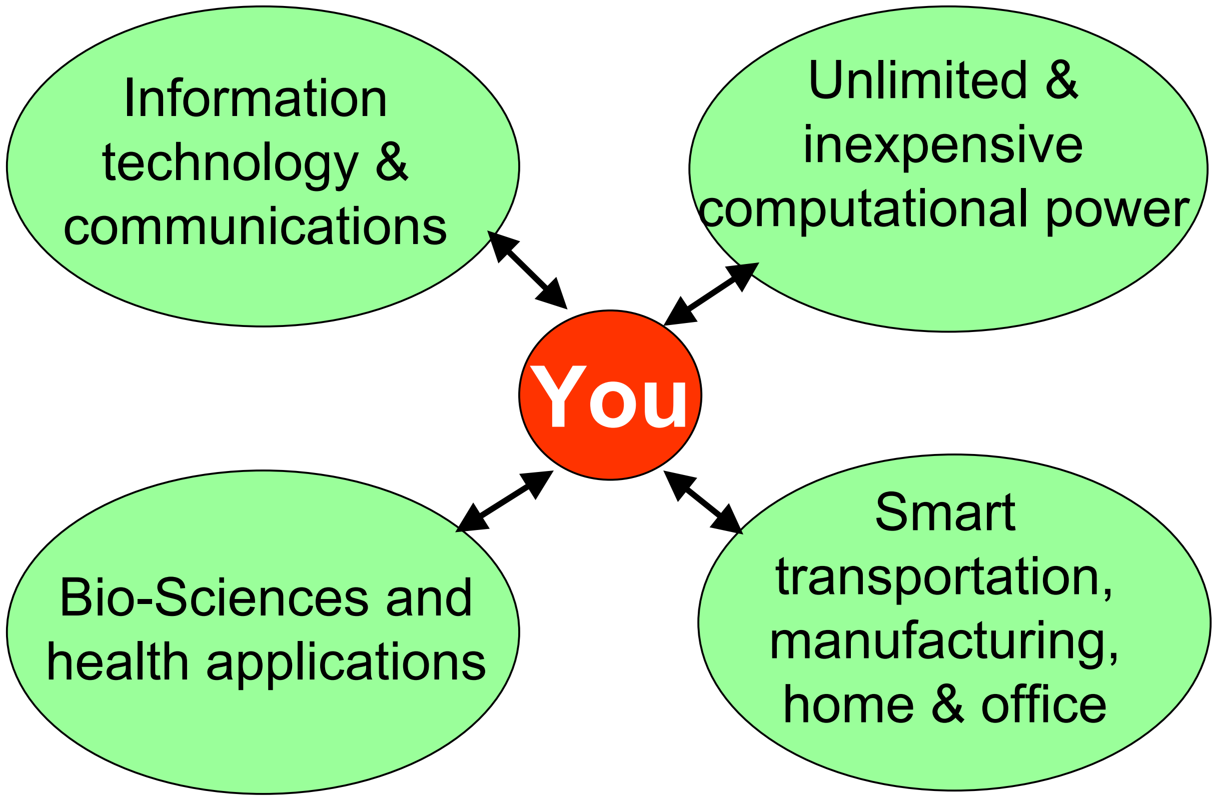
The environment



Relies on continued scaling of technology

What is next?

- Scaling of present CMOS technology will continue aggressively until a true limit is uncovered
  - ➤ Increasingly complex technology and materials choices
  - ➤ The International Technology Roadmap for Semiconductors (ITRS) has made projections to 2016
- Component & system architecture will play an increased role in performance improvement and product differentiation
  - ➤ Less reliance on very fast transistors
  - ➤ Plenty of room for better architectures

For ITRS information, log on www.src.org

What is next

- The semiconductor industry is already operating in the deep nanometer scale
  - 1.2nm gate oxides are in production today
  - Operation of transistors down to 15-20nm have been demonstrated (2-3 generations ahead)
  - Started using 1-D self assembly concepts like ALD

- The challenge is to successfully integrate new materials and technologies. Some examples:
  - High K gates to overcome the leakage problem
  - Advanced transistor architectures for performance increase
  - Novel package concepts to address the power & cooling limitations

What is next

- Technology is becoming more diverse to address the needs of the environment
  - ➤Micro Electrical Mechanical Systems (MEMS) and System On a Chip
    - – Integration of Sensors, Computation, Actuators, Communication
  - ➤Electrical←→Optical conversion for communications
  - ➤Convergence of Microelectronics and the Bio-Sciences

What is next

- Novel concepts and materials are being proposed (often referred loosely as nanotechnology)
  - ➤ Self Assembly concept. Prevalent in living organisms
  - ➤ Materials with highly interesting properties like Carbon Nanotubes
  - ➤ Molecular electronics
- While highly appealing because of the extraordinary properties that they display, large obstacles remain for them to become alternatives to Silicon technology any time soon

The Self Assembly concept

- A highly appealing concept modeled after living organisms
  - ➤ Relies on smart chemistry and molecularly stored blueprints like DNA

Traditional: Patterning	Self Assembly
• Top-Down approach • Scaling of layers from bulk dimensions • Atomic & molecular granularity is generally an obstacle • Complexity & cost is scalating exponentially ($20M for EUV system)	• Bottoms up approach • Self assembly of atoms & molecules into useful structures • Atomic & molecular granularity and distinct properties are an opportunity • Requires a molecular blueprint for assembly • Living organisms and the brain are superb examples of efficient, self assembling, self replicating, high performance, defect tolerant, low power, inexpensive systems

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The limits of computation

Power cost of information transfer?
After Richard P. Feynman

ν = 10^{18} *bit-ops/sec*

For P = 1 Watt

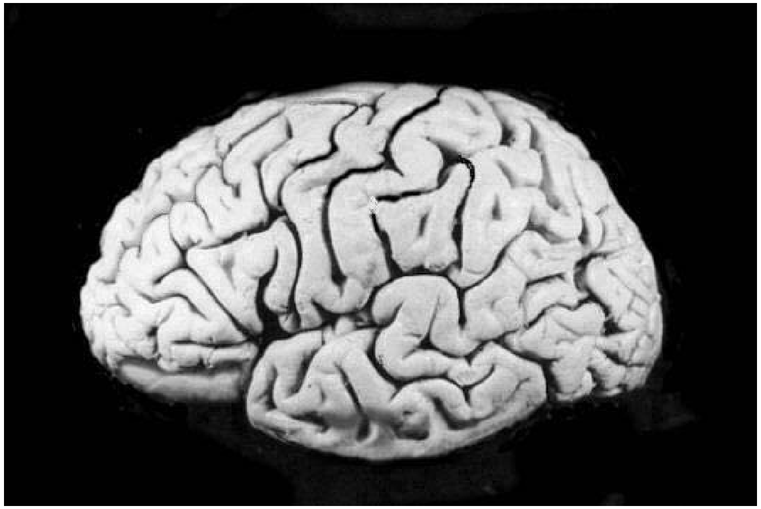
About 1 billion Pentium Processors

in a hand-held device!

We have a long ways to go

Edwards (HP): Presentation on
Molecular electronics, 2001

Alternative computation models



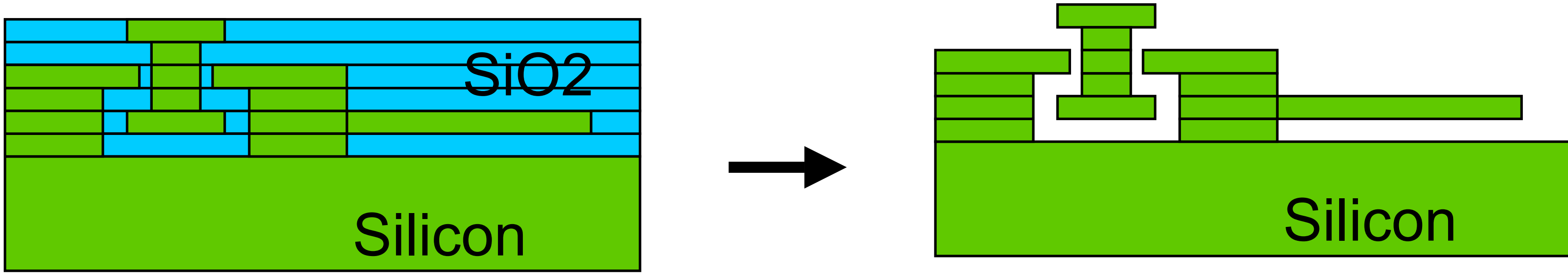
The brain is the ultimate model for its ability to deal with complexity

- Little understanding on its architecture & organization
- It is however
  - ➤ Orders of magnitude more powerful than the best microprocessor
  - ➤ Self assembled
  - ➤ Parallel operation
  - ➤ Self repairing to a significant degree
  - ➤ Fault tolerant
  - ➤ Runs on ~ 10W

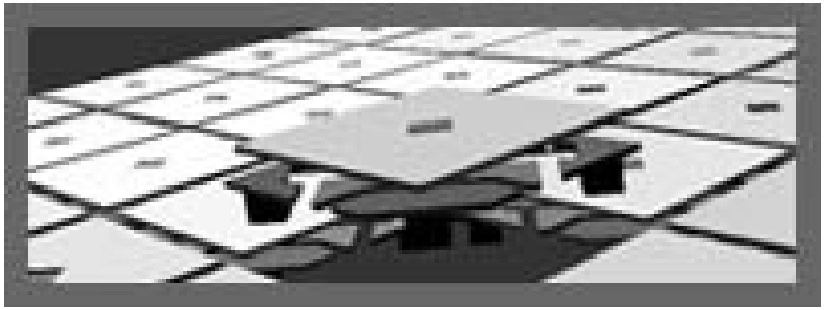
Some interesting examples

- The case for MEMs and System on a Chip
- Carbon nanotube devices
- Molecular electronics

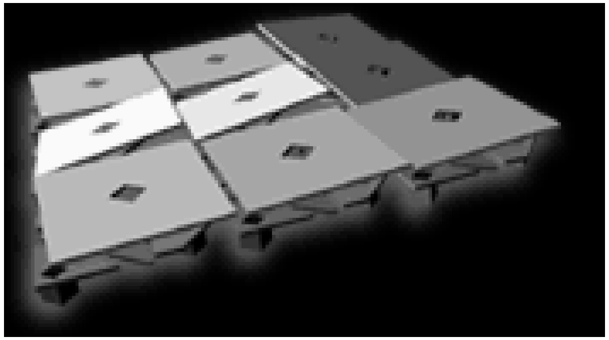
Some MEMS examples
Micro Electro Mechanical systems



- CMOS Silicon compatible technology



16μm X 16μm mirror elements



DLP™ by Texas instruments

- A DLP™ micro-mirror array likely used in the projector making this presentation possible

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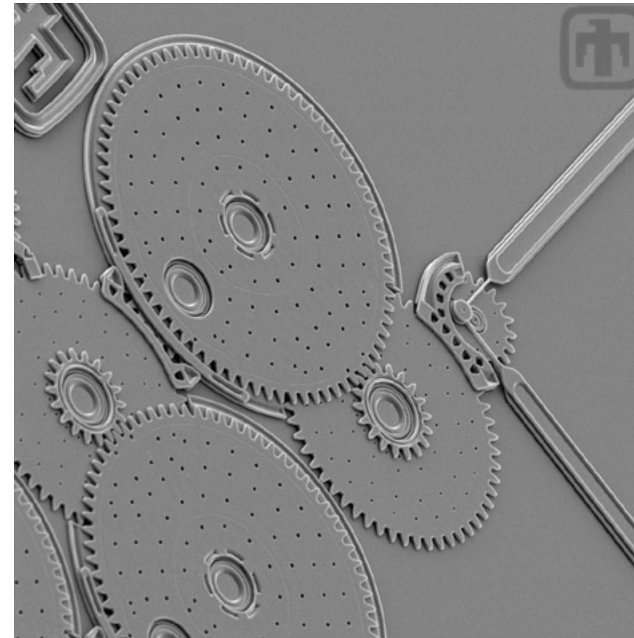
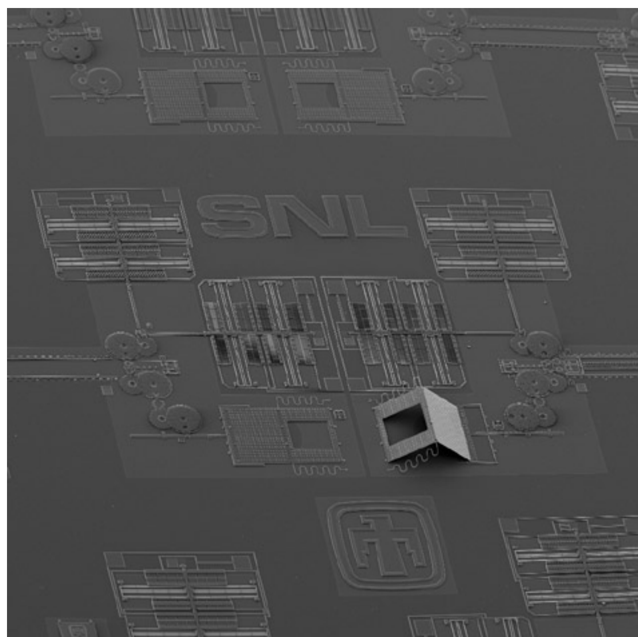
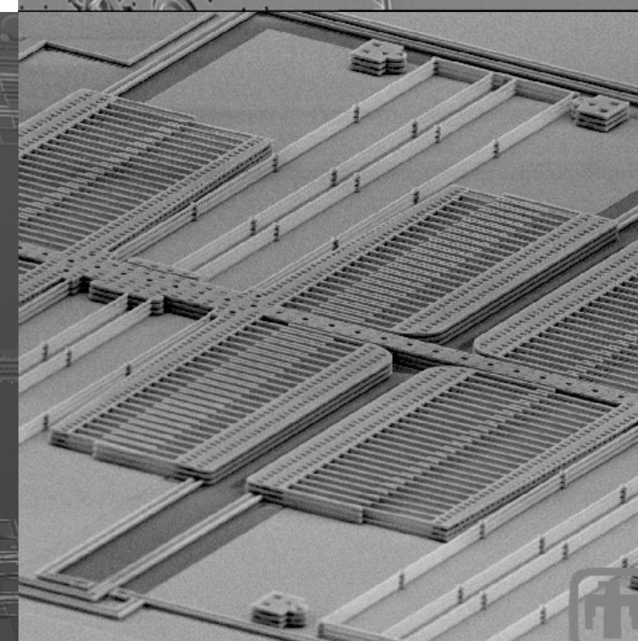
Some MEMS examples

- Sensors, actuators, RF switches, RF Filters, optical devices & many other components have been demonstrated
- Integrating them with CMOS forms the basis of System on a Chip







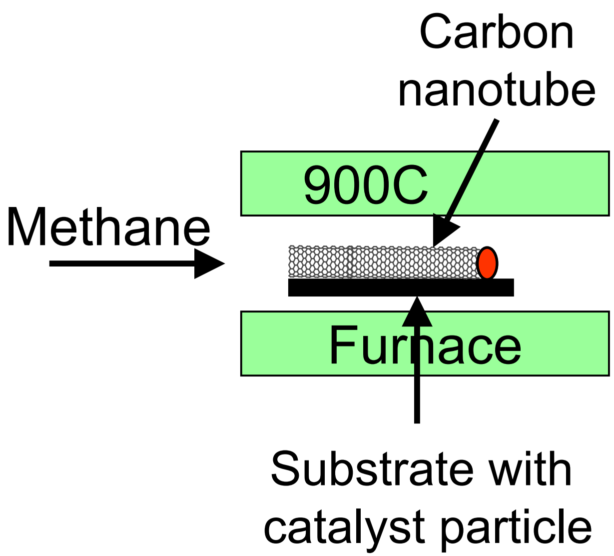
Courtesy:
Sandia National Labs
www.sandia.gov

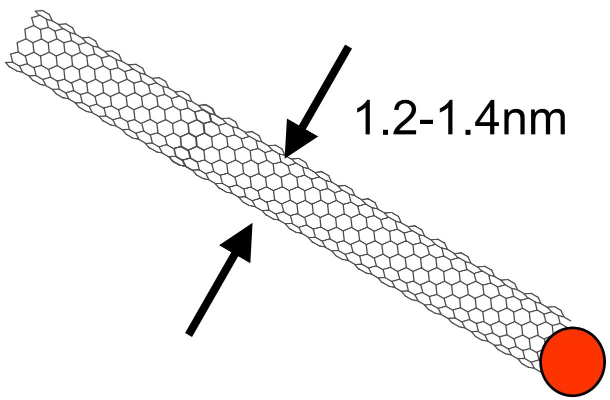
MEMS to BioSciences convergence

- Many proposals have been made, from microfluidics to DNA sequencers.
- The field is just opening up. Large number of devices & products expected in the near future

Carbon Nanotubes

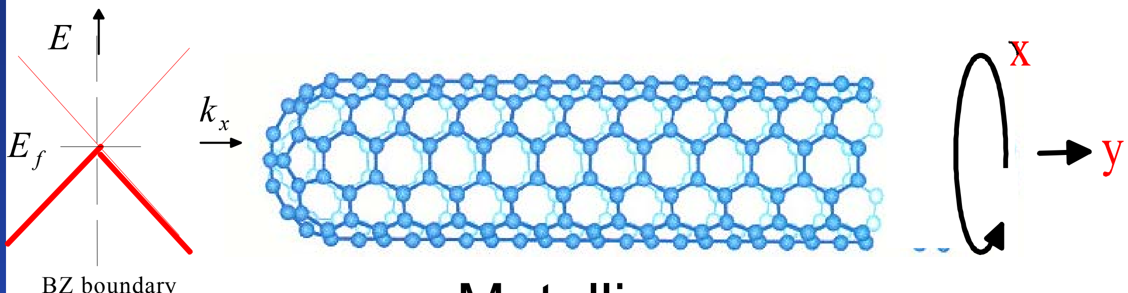
- Discovered in 1991 by S. Iijima. Nature 354, 56 (1991)
- Long, thin cylinders of Carbon with remarkable physical properties
- They can be thought of as a sheet of graphite (a hexagonal lattice of carbon) rolled into a cylinder
- They self assemble





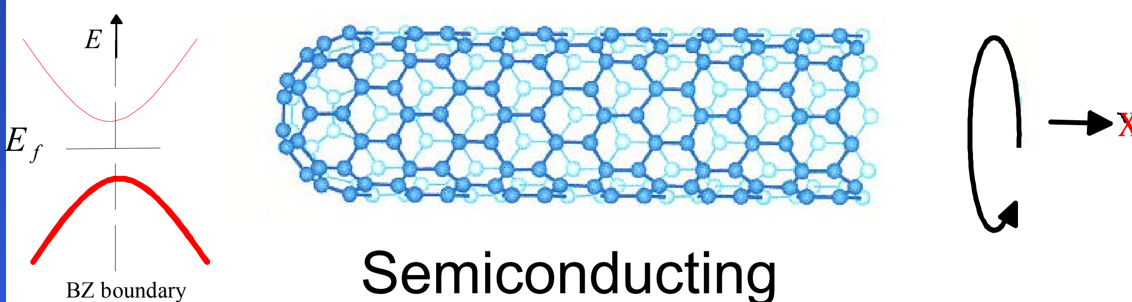
Bokor, Dai, McEuen, Quate Marco Review, April 2002

Nanotubes



Metallic

- Resistivity comparable to best metals
- Ultrahigh current densities



Semiconducting

- Very high mobilities
- Very high transcond.

- Strongest material known

Bokor, Dai, McEuen, Quate Marco Review, April 2002

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Physical properties of nanotubes

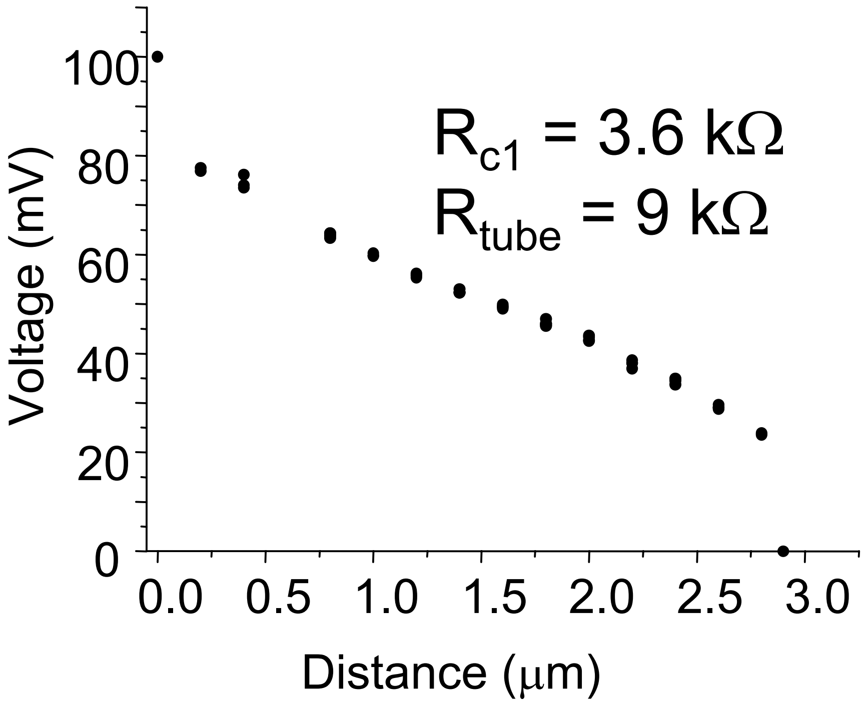
Property	Value	Reference
Average Diameter	1.2 - 1.4 nm	
Density	1.3 - 1.4 g/cm3	
Energy Band Gap (metallic)	0 eV	
Energy Band Gap (Semiconductor)	0.5 eV	1.1 eV for Silicon
Resistivity	1E-4 - 2E-6 ? cm	1.7E-6 for Copper
Maximum Current Density	1E9 A/cm2	1-3E6 A/cm2 for Cu (IC)
Thermal Conductivity	~ 2000 W/m-K	
Phonon mean free path	100 nm	10 nm for Silicon
Young's Modulus SWNT	~ 1TPa	
Young's Modulus MWNT	~ 1.3 TPa	
Maximum Tensile Strength	30 Gpa	

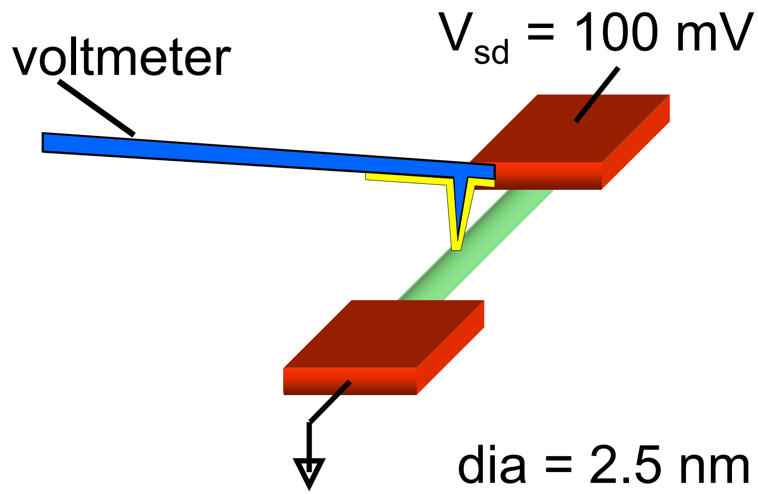
Compilation of properties by Adams @ ww.pa.msu.edu/cmp/csc/nanotube.html

- Light, flexible and 100X stronger than steel
- Thermal conductivity of diamond
- Electrical conductivity of copper, with
  - 1000X higher maximum current density

Will surely find uses for such remarkable properties

Metallic Nanotubes



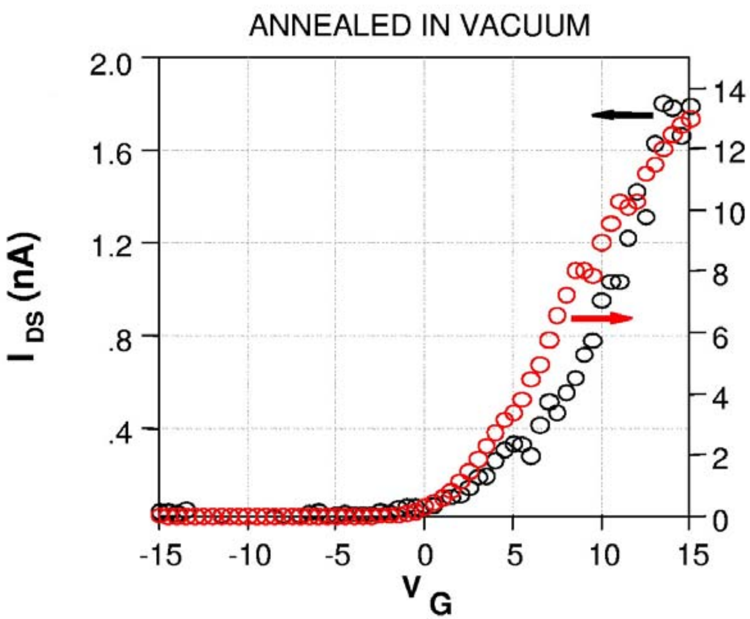


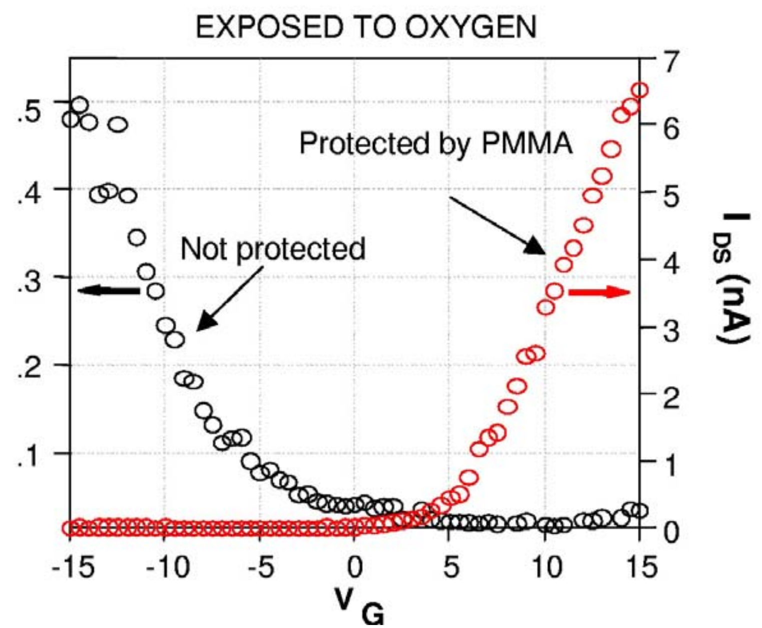
Parameter	Value
R_{tot}	16.3 kΩ
R_{tube}	9 kΩ
R_{c1}	3.6 kΩ
R_{c2}	3.7 kΩ
I_{max}	60 μA
R_{tube} /L	3kΩ / μm
ρ	2 x 10^{-6} Ω-cm
j	10^9 A / cm^2

Bokor, Dai, McEuen, Quate

Marco Review, April 2002

Can be made into N & P type semiconductors





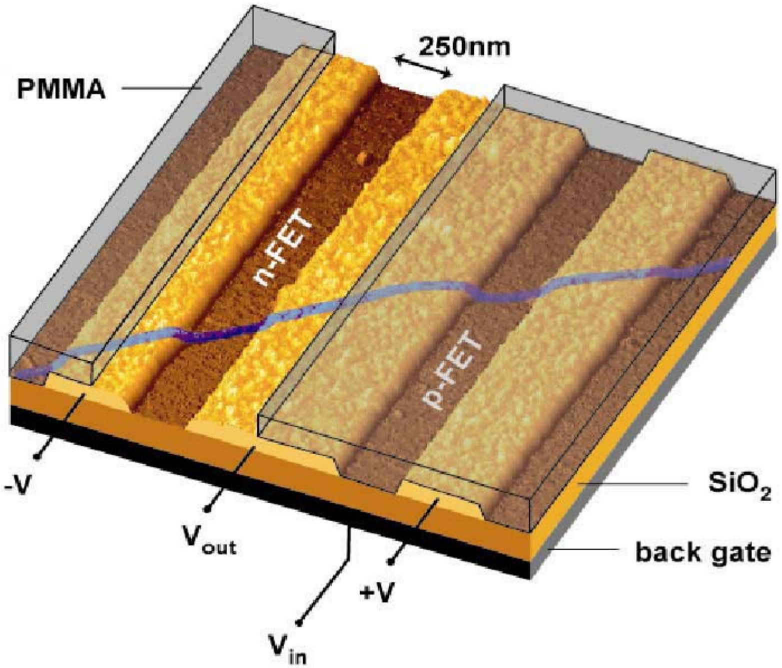
N-type by:
- Annealing in vacuum
- Doping with K

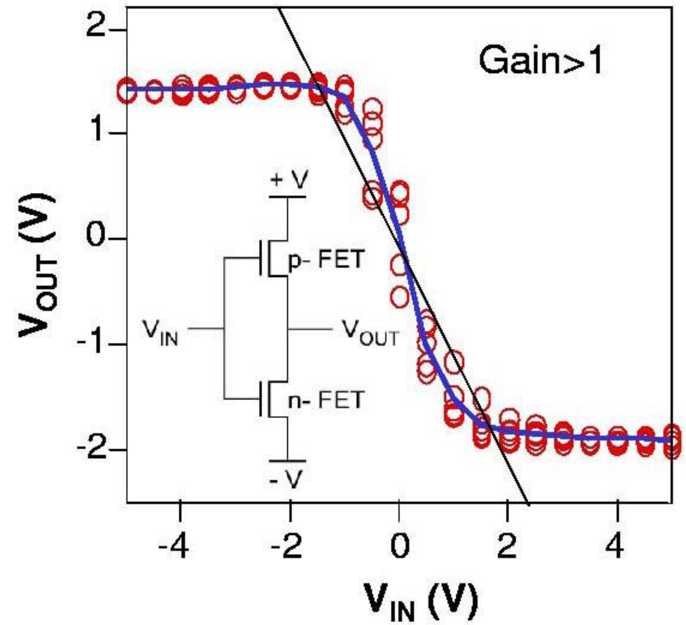
P-type by exposing to Oxygen

Derycke et al. @ www.ibm.com/research

- Key building blocks for semiconductor devices

Which allows fabricating CMOS inverters

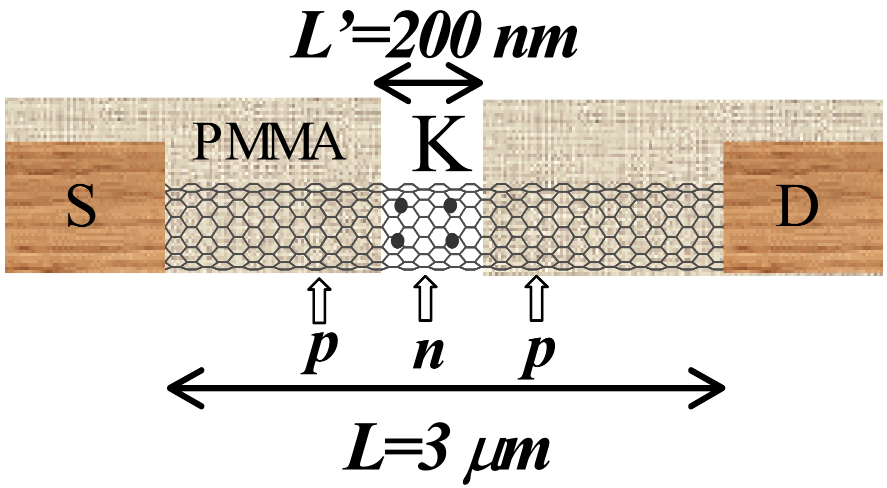


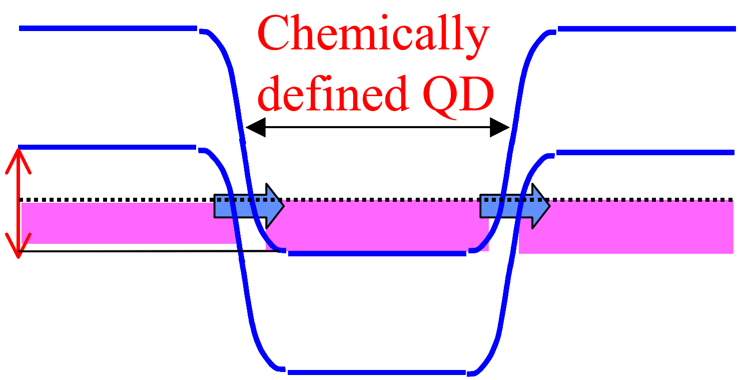


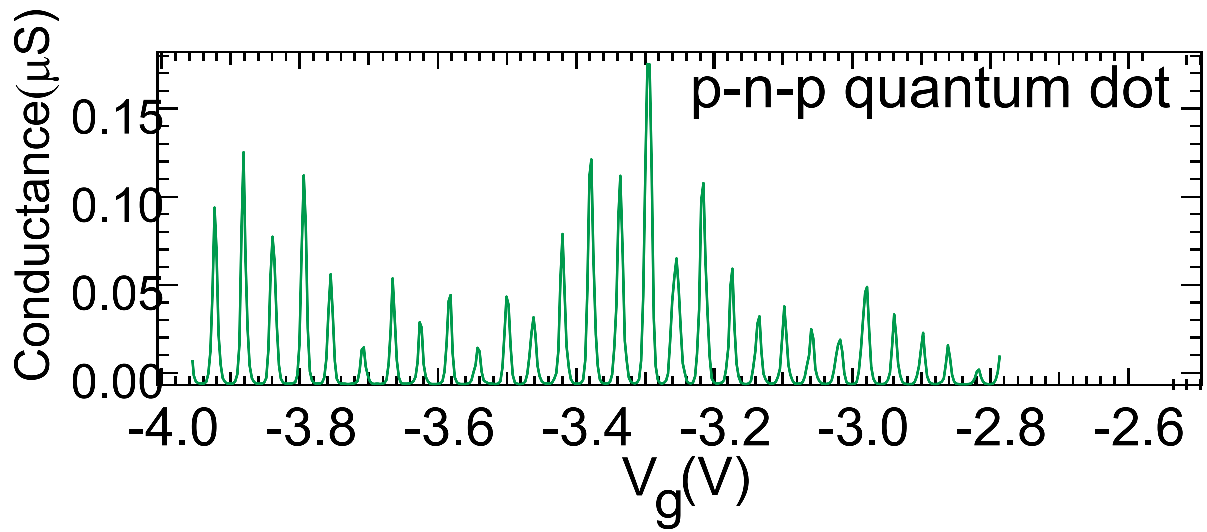
Derycke et al. @ www.ibm.com/research

- Inverters and similarly fabricated NOR & NAND gates are the key components of of the most common computer chips

And Quantum dot devices







Bokor, Dai, McEuen, Quate Marco Review, April 2002

Carbon Nanotubes

- They have remarkable properties
- Very large obstacles remain for their useful implementation as transistors
  - ➤Consistently building metallic or semiconducting CNT. (controlled by chirality)
  - ➤Controlling the direction of growth and their positioning to achieve the desired functionality
  - ➤Electrical contacts are fairly high resistance (KΩ)
  - ➤They grow very long (μm)

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Nanoelectronics Reseach centers
An incomplete list

US Gov labs

- Dept. of Defense
- Naval research Lab
- Los Alamos Nat Lab

US Universities

- UCLA
- Cornell
- MIT
- U. of Minnesota
- Notre Dame
- Penn State
- Purdue
- Stanford

US funded R&D centers

- The Aerospace Corp
- MIT Lincoln Labs
- MITRE
- RAND

European Labs

- U of Berlin
- Cavendish Lab
- U. of Glasgow
- IBM-Zurich lab
- Nat. Phys. Lab. Teddington, GB
- U. College, London

Molecular & Organic electronics

- Actively being investigated for transistors, memory devices, optoelectronics and displays
- Many molecules have been identified and are under study
- Some have hysteresis suggesting potential uses as Non Volatile Memory devices
- Many have fluorescent or phosphorescent properties
- Methods for self assembly of single molecular layers proposed
- May prove useful for low performance, low cost, large area fabrication

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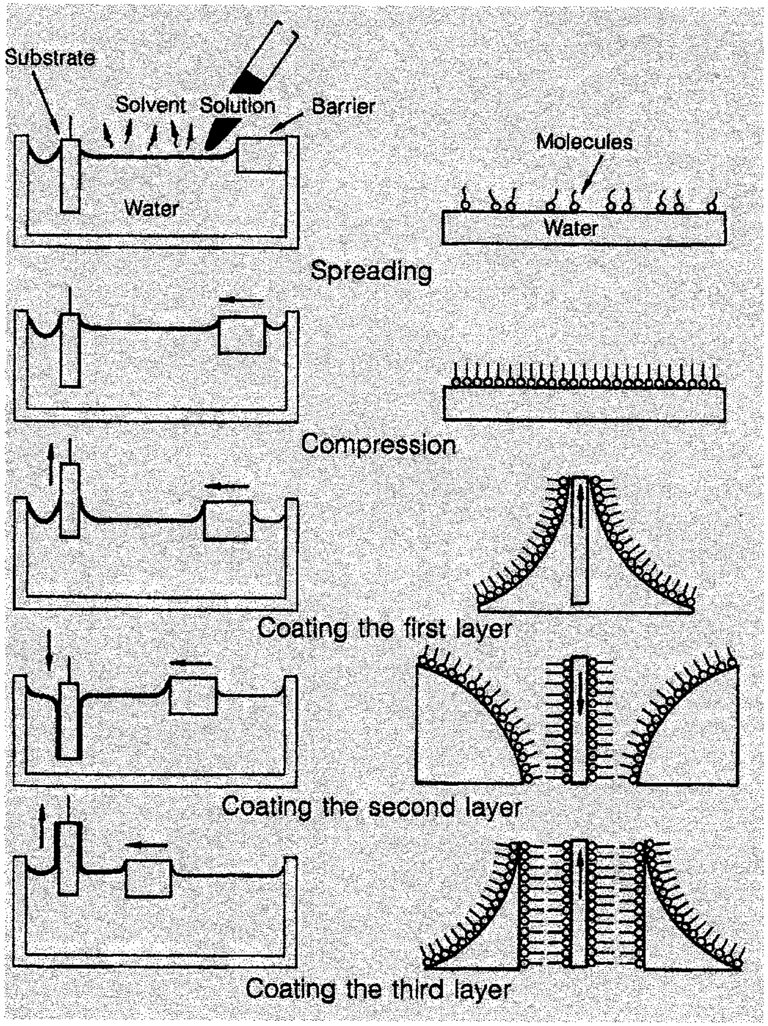
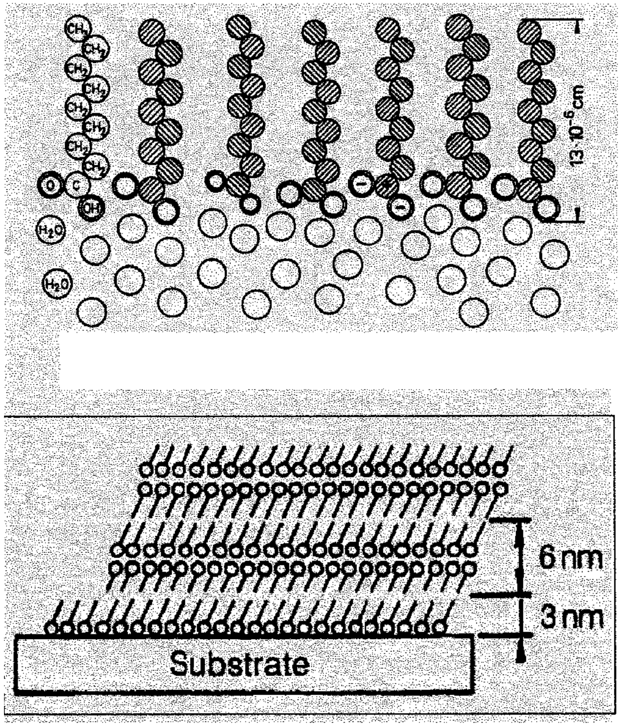
Self assembly of molecules

Langmuir-Blodgett deposition



Fatty acid molecules on an aqueous surface



Adapted from V. Bulovic @ MIT

Molecular transistor concept
An example

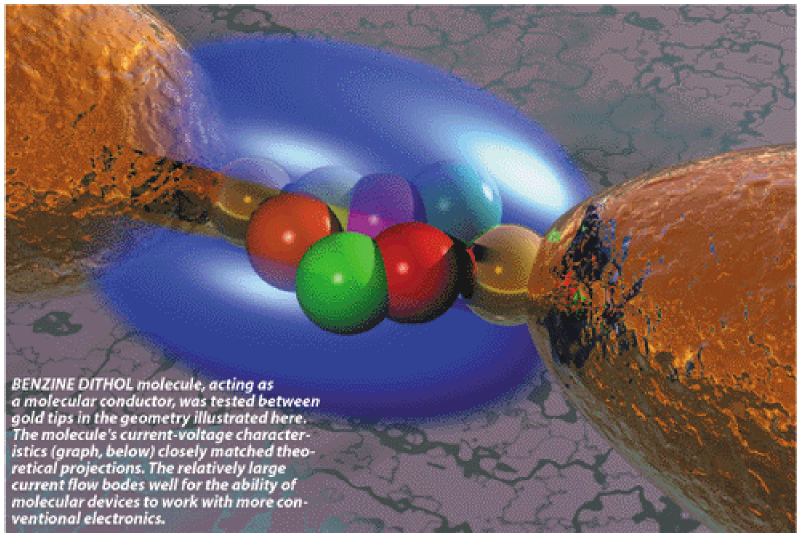
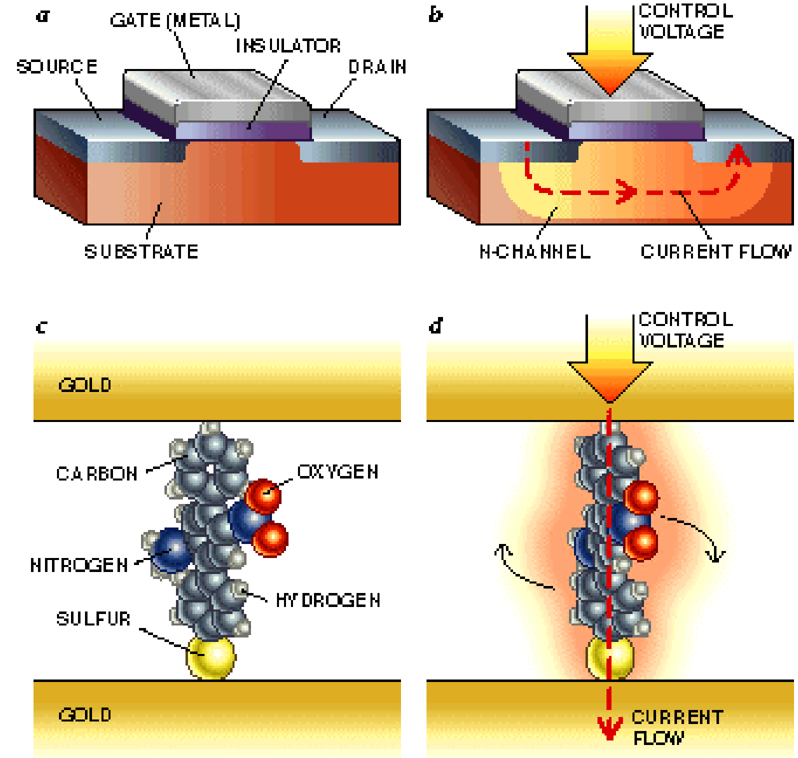


Illustration: Jared Schneidman
See M. Reed et al. @ Scientific American, June 1999

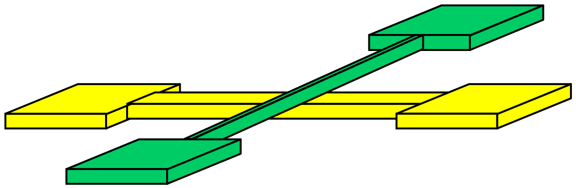


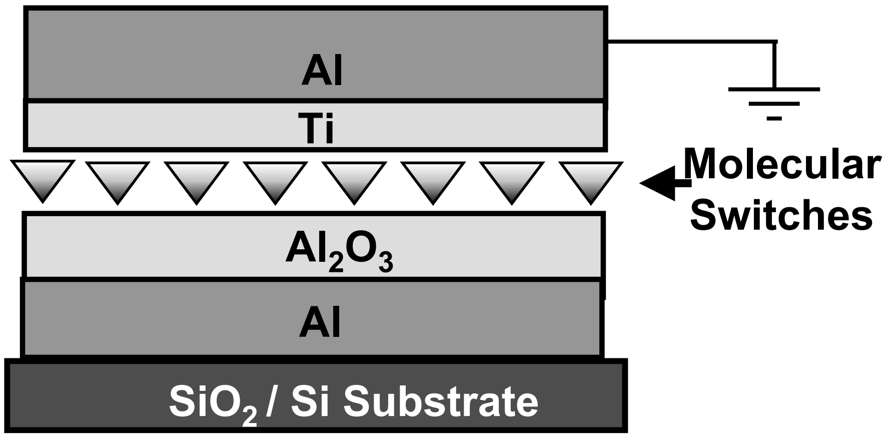
CONVENTIONAL MICROTRANSISTOR (a) has three terminals, known as the source, gate and drain. A positive voltage applied to the gate draws electrons to the insulator (b), enabling current to flow from the source to the drain. A molecule based on three benzene rings (c) was also used to switch an electric current. The center ring had asymmetric fragments, enabling it to be twisted by an electrical field (d). With a specific voltage applied, the electrical field twisted the molecule and permitted current to flow.

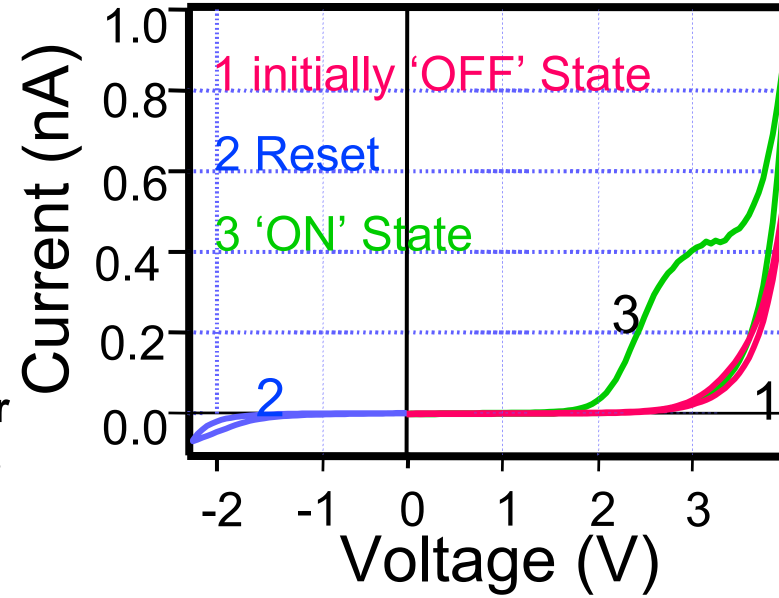
For an all polymer integrated circuit example see:

Drury et al., Appl. Phys. Lett. 73< 108 (1998)

Memory device concept







Eicosanoic Acid ($C_{20}O_2H_{40}$)

Basic device elements:

- Monolayer molecular film: 0.5-3nm
- Electrodes

Edwards (HP): Presentation on Molecular electronics, 2001

Polymer Film Memories & Devices

- A large variety of devices & film compositions have been proposed
- Most are based on bulk organic film materials and are not to be confused with self assembly schemes
- They may result in practical devices earlier than the self-assembled molecular films
- They generally rely on standard patterning techniques, and therefore have the same general scaling advantages & disadvantages than standard silicon devices

Organic film Optoelectronics and displays & devices

Many devices proposed or demonstrated

• Polymer memories	Intel & others
• Organic solar cells:	Peumans et al, Appl. Phys. Lett (2000)
• Photodetectors:	Peumans et al, Appl. Phys. Lett (2000)
• Luminescent Organic films:	Bulovic et al, Chem. Phys. Lett. 308, 317 (1999)
• Organic lasers:	Kozlov et al, Nature 389, 362 (1997)
• Displays:	Kodak, Sanyo, Universal Display Corp.

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Summary

- Scaling of conventional CMOS will continue aggressively until a true limit is encountered
  - ➢The key challenge is integration of new materials & technologies
  - ➢Need aggressive innovation in Component & System architectures
- Technology needs are becoming a lot more diverse
  - ➢MEMS/SOC, Electrical to optical conversion & intersect with biosciences
- Exciting novel materials & concepts are being proposed
  - ➢Self assembly techniques are in their infancy but will have a large impact in the long run
  - ➢Remarkable properties but still far away to challenge mainstream technology.
  - ➢As they become ready, they will likely complement the mainstream and be incorporated to Silicon technology rather than replace it

Thank You

Eskerrik Asko

Muchas Gracias